REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE -	3. REPORT TYPE AND DATES COVERED FINAL 10 Jul 95 - 09 Jul 99

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Ultra-High Density Recording	DAAH04-95-1-0474
6. AUTHOR(S) Prof. Mark H. Kryder	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Carnegie-Mellon University	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 34644.1-RT-AAS

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

Research on ultra-high density optical recording systems funded by the U.S. Army Research Office was conducted at the Data Storage Systems Center at Carnegie-Mellon University. The goal of this reasearch was to supplement a broader DSSC effort to investigate optical recording technologies that could lead to ultra-high recording densities. The work was directed at developing an understanding of the cyclability of phase change media, the fabrication of solid immersion lens, the development of improved integrated engineering test beds, and the evaluation of different optical media structures.

14. SUBJECT TERMS	15. NUMBER OF PAGES 9
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

A National Science Foundation
Engineering Research Center
at Carnegie Mellon University

Data Storage Systems Center
Carnegie Mellon University
Pittsburgh, PA 15213
(412) 268-6600
www.dssc.ece.cmu.edu

Data
Storage
Systems
Center

ULTRA-HIGH DENSITY OPTICAL RECORDING

FINAL REPORT

7/10/95-7/8/99

U.S. Army Research Office

Grant DAAH04-95-1-0474

Prof. Mark H. Kryder, Principal Investigator

Professor Robert M. White, Director
Dr. Horacio A. Méndez, Executive Director

Ultra-High Density Optical Recording

U.S. Army Research Office Grant DAAH04-95-1-0474

Prof. Mark H. Kryder, Principal Investigator
Period of Research July 10, 1995 to July 9, 1999

Executive Summary

Research on ultra-high density optical recording systems funded by the U.S. Army Research Office was conducted at the Data Storage Systems Center at Carnegie Mellon University. The goal of this research was to supplement a broader DSSC effort to investigate optical recording technologies that could lead to ultra-high recording densities. The work was directed at developing an understanding of the cyclability of phase change media, the fabrication of solid immersion lens, the development of improved integrated engineering test beds, and the evaluation of different optical media structures.

A study to identify the factors limiting the cyclability of phase change optical media has shown that cyclability is effected by the extent to which a recorded optical spot is heated when it is repeatedly written and erased. This was demonstrated by the effect of both higher write powers and higher media velocities. At higher write powers, cyclability was found to be reduced at comparable erase powers and to be significantly improved at higher media velocities for comparable write power levels. Even though the cyclability of the media did improve at higher velocities for comparable write powers, however, the cyclability did degrade even at higher velocities for high write powers. Thermal conductivity, which influences the amount of thermal interference that exists between adjacent bits, was also shown to change with repeated overwrites. A technique was developed, using the reflectivity of the media as a function of temperature and the radius of the crystallized spot, to calculate thermal conductivity during the read or write process.

A research effort to design, fabricate and implement a super-solid immersion lens system has allowed Center researchers to successfully develop the ability to fabricate SILs, both hemispheres and superspheres. An optical assembly with a numerical aperture of 1.8 was constructed using these lens and theoretically predicted spot sizes have been demonstrated. In a related effort, a new method was developed to measure extremely small optical spots of least than 200 nm FWHM in the near field.

The capabilities of a blue wavelength optical spin stand have been improved and optimized to assist in the development of ultra-high density recording technologies. The ability to achieve acceptable carrier to noise performance has been accomplished through through the identification and correction of gas laser low frequency modulation noise. In addition, an upgraded electro-optic modulator allowed for improved control of laser

intensity modulation, which permitted the development of an automatic testing procedure for the blue wavelength spin stand, and the development of a focus servo system, provided for multi-layer testing of experimental media. Throughout the course of meeting the hardware requirements for the improvement and optimization of the blue wavelength optical spin stand, many samples of experimental magneto-optic, multilayer phase change and MSR media were tested, characterized and reported.

I. Introduction

The Data Storage Systems Center at Carnegie Mellon University was awarded funding of $175,996 over three years by the U.S. Army Research Office to support the DSSC research effort in advanced ultra-high density optical recording technology (Grant DAAH04-95-1-0474). The goal of this research was to supplement a broader DSSC effort to investigate optical recording technologies that could lead to ultra-high recording densities. This specific project was directed at developing an understanding of the cyclability of phase change media, the fabrication of solid immersion lens, the development of improved integrated engineering test beds, and the evaluation of different optical media structures.

The original period of performance was from July 10, 1995 to July 9, 1998. This research became delayed due to the changing technical foci on the part of the industrial firms who were contractors on related DARPA projects on which the DSSC was working. These changes caused the Center to support additional graduate students who were not immediately available. As a result, a one-year extension was awarded, extending the period of performance to July 9, 1999.

The goal of the overall optical recording program at the DSSC is to advance the technologies which will enable optical storage to take a substantial place in the data storage market. In particular, this goal includes achieving shorter access times, higher data rates, and higher areal densities. Efforts are focused on what is believed to be the most critical technical problem areas: short wavelength optical media, new optical head and actuator technology, advanced signal processing techniques, servo algorithms, and systems integration to permit evaluation of new developments in these areas in actual spin stand tests.

In the area of optical media for ultra-high density recording, Center researchers are focusing on the development of an understanding of how film composition, processing and microstructure affect media performance in terms of signal-to-noise and of a medium structure capable of providing adequately high resolution and adequate signal-to-noise at ultra-high densities. These include phase change and magnetic-optic media and magnetic amplified magneto-optical systems (MAMMOS). The project covered in this report focuses on the study of the cyclability of phase change media.

The central theme for the DSSC's research on optical heads is to minimize the size and mass of the optical components which have to be moved across the surface of a disk, while at the same time, producing spot sizes below the diffraction limited sizes associated

with far-field optical systems. Another important technique being explored for achieving ultra-high density optical data storage involves the use of a solid immersion lens (SIL) and apertured systems and the demonstration of these systems on a blue light spin stand. The Center has pursued theoretical studies of the fields in the focal plane of such lenses with the goal of better understanding the nature of the near-field coupling between the fields in the lens and the medium. One of the goals of this project area is to fabricate SIL systems capable of producing spots of size <200 nm and measure them. The project covered in this report focuses on the design, fabrication and implementation of a super-solid immersion lens head.

Systems integration efforts at the DSSC include the development of use of optical disk engineering testbed spin stands for characterizing and demonstrating integrated operation of optical heads, media and electronic systems. The project covered in this report focuses on the optimization of a blue wavelength optical spin stand for the evaluation of new component technologies.

II. Research Accomplishments

Studies of Phase Change Media for Ultra-High Density Optical Recording Cyclability

One of the goals of the DSSC's research in optical media is to develop an understanding of how film composition, processing and microstructure affect media performance in terms of signal-to-noise and to create a medium structure capable of providing adequately high resolution and adequate signal-to-noise at ultra-high densities. The project covered in this report focuses on the study of the cyclability of phase change media.

Phase change optical recording has the advantages of relative ease with which overwrite may be done, compatibility with DVD ROM, high signal strength and uncomplicated optical heads. These features enable realization of low cost and reliable read/ write drives. The main drawback that phase change recording has suffered from, is the limited number of write/erase cycles. The objective of this research effort was to identify the factors limiting cyclability and study how the media properties were affected in the process of repeated overwrites. This research included determining the thermal parameters of the phase change media, which if estimated as a function of the overwrite cycles, provides improved insight into the mechanisms that limit cyclability.

Phase change recording makes use of the amorphous and crystalline structural states (phases) to encode data. The read out mechanism is based on the difference in reflectivities between the two phases. Direct overwrite can be accomplished by switching the laser between the write and erase power levels and the areas irradiated by these power levels will be turned amorphous and crystalline, respectively. It is widely known that the CNR available from a disk can be increased with an increase in the write power. However, not much attention has been given to studying the effects of higher write powers on the cyclability of the media. The effect of media velocity on the erasability has been looked into [1,2] but not the effect on the cyclability of the media. In this research, we studied the effects of write power and media velocity on the cyclability of phase

change media. For the first time, we were able to stroboscopically image the dynamics of the write process on phase change media with a 10 ns exposure time high speed stroboscopic camera [2]. The samples that were used for the studies were provided by Imation.

For these experiments, the phase change disk was made to spin on an air bearing spindle, the rotation of which is synchronized with a write/ erase laser at 840 nm and a 10 ns pulse width observation laser at 460 nm. A lens with a NA of 0.6 was used to focus the beams onto the disk. The IR laser was driven between the write/ erase power levels in such a way that spots were written in alternate cycles and erased in the others; repeated write/ erase of the same spot could thus be achieved. The observation laser pulse could be positioned at any time with respect to the write laser pulse with a resolution of 10 ns to stroboscopically image the write process.

The images were captured by a high-speed camera which was also synchronized with the rest of the system. The experiments were carried out for different pulse widths at different write powers and two different media velocities of 4.7 m/s and 9.4 m/s. The dynamic write process of a 300 ns pulse and a 200 ns pulse were imaged at intervals of 100 ns and 50 ns respectively, starting from 100 ns before the write pulse to 100 ns after the write pulse. Images were taken approximately 60 write/erase cycles after the IR laser started firing and the same spots were then imaged after approximately 1200 cycles to observe the difference in recording process after repeated write/ erase cycles. At 4.7 m/s, images for a 300 ns pulse were taken for write powers of 6.25 mW and 6.75 mW. The erase power was kept fixed at 3.6 mW throughout the set of experiments. This was done since even the spots written with higher powers were getting erased initially with this erase power. At the higher write power, the write spot did not get erased even after 60 cycles. However, after about 1200 cycles, it was seen that the erasability became worse at both power levels, but the effect was much more severe for the higher write power. Thus the cyclability was reduced at higher write powers even though the CNR may be higher.

We then imaged the write process of a 300 ns pulse at 9.4 m/s with write powers of 7.5 mW and 8.0 mW. For comparable power levels, we found that the cyclability was much better at a higher media velocity. By comparable powers, we mean the minimum power required to write the amorphous spots at the two velocities and the increments thereof. Though the velocity had been doubled, the powers were not increased by the same amount, and, consequently, the thermal energy was smaller at the higher velocity. We carried out similar experiments for a 200 ns pulse with write powers of 6.0 mW and 6.5 mW at 4.7 m/s and with write powers of 7.8 mW and 8.4 mW at 9.4 m/s. The results were consistent with those using a 300 ns pulse. It was seen that even though the cyclability could improve at higher velocities for comparable power levels, the cyclability did degrade even at higher velocities for high write powers. These results suggest that the extent to which a spot is heated when it is repeatedly written and erased affects the cyclability; this is seen from the effect of higher write powers as well as from the effect of media velocity.

In addition to understanding the dynamic writing and amorphization process, knowledge of the thermal parameters, thermal conductivity and specific heat are also required to study the thermal profiles in the phase change media. Thermal conductivity, which influences the amount of thermal interference that exists between adjacent bits, changes with repeated overwrites. The material properties of thin films differ from the values in bulk. Even though there were simulation tools available for the study of the temperature profiles in recording media, there was no established experimental method to determine the thermal parameters of thin film optical recording media. The thermal coefficients have been determined using some experimental data and simulations by Cheng et al [3]. The crystallization phenomena in phase change materials have been studied by many groups [4,5,6] but these have been static studies and/or simulations.

Since the temperature at the disk surface cannot be measured directly during the read or write process, the reflectivity of the disk was measured as a function of the temperature, for the amorphous to crystalline transition. A crystalline mark was then written on the disk with dc laser irradiation and the mark was imaged while the laser power was on. It was seen that the mark size attained a steady state even though the laser was on for several tens of seconds. The constant reflectivity contours of the written crystalline mark, which correspond to isotherms, were then determined using image processing. This was then used along with the reflectivity vs. temperature plot, measured earlier, to extract the temperature distribution as a function of the radius of a crystallized spot. The thermal conductivity value was then solved by using the heat equation in the steady state and the temperature distribution. The media used in the study was $ZnS\text{-}SiO_2$/ $Ge_2Sb_2Te_5$/ $ZnS\text{-}SiO_2$/ AlCr/ Glass substrate. A value of $0.011\ Wcm^{-1}K^{-1}$ was obtained for the thermal conductivity.

In this research, only static measurements were used. To be able to determine the specific heat of the phase change media, as well as to be able to determine the nature of the evolution of the thermal properties with repeated overwrites, one also needs to be able to measure the dynamics of the amorphous to crystalline transition. Therefore, future work in this area will include near field recording studies using phase change media and the use of a solid immersion lens optical head. In addition, studies of the dynamics of the crystallization process will also be done to help determine the crystalline growth velocity, which affects the maximum possible data rates.

Fabrication of Solid Immersion Lens Heads for Ultra-High Density Optical Recording

One of the goals of the DSSC's optical recording program is to fabricate solid immersion lens (SIL) systems capable of producing and measuring spots of size <200 nm, to develop apertured SIL and apertured lasers and to demonstrate these systems on a blue light spin stand. Experimental verification of the Center's modeling of the performance of a SIL, which demonstrated that focusing the beam spot beyond the plane at which the minimum spot is desired results in a minimum spot on that plane, is another area of interest.

This research effort has been directed toward designing, fabricating and implementing a super-solid immersion lens system. Designing the super-SIL required a careful choice of

parameters such as readout laser wavelength, objective lens, and glass sphere characteristics. The readout laser wavelength affected the design in numerous ways. First, the index of refraction of the materials is a function of wavelength. Second, the amount polished off of the sphere to form a super-sphere depends on the index of refraction of the sphere and thus the wavelength of the readout laser. An aspheric objective lens with a maximum numerical aperture of 0.55 and a working distance of 2.9 mm was chosen for this assembly. An aspheric lens was chosen to minimize spherical aberration. The numerical aperture of the lens was chosen such that the effective aperture of the system would not exceed the index of refraction of the material (n=1.86) for a blue wavelength (λ=488 nm) readout laser. The working distance was chosen to allow room for the super-sphere between the focal plane of the lens and the lens. A glass sphere with a diameter of 2 mm was chosen to be fabricated into the super-sphere.

Fabrication of the super-SIL required polishing of the glass sphere into a super-sphere and manufacturing a mounting system for the objective lens and the super-sphere. The glass sphere was polished such that the distance from the center of the sphere to the flat polished surface is equal to r/n where r is the radius of the sphere and n is the index of refraction of the material. This was accomplished with a polisher at Carnegie Mellon University. The final grade of polish was 0.03 •m which yields a scratch and dig better than •/10. The mounting system was designed to maintain proper alignment between the super-sphere and the objective lens. However, the mount is threaded to allow fine-tuning of the distance between the objective and the super-sphere, which allows the smallest spot size to be achieved.

Future work will include the design, fabrication and integration of an apertured-SIL onto the blue wavelength optical spin stand. The apertured-SIL could allow spots as small as 50 nm to be recorded and read back successfully. The intensity profile and polarization fields out of the apertured-SIL should be modeled to compare with experimental results.

Development of Engineering Test Beds for Ultra-High Density Optical Recording

The capabilities of a blue wavelength optical spin stand were improved and optimized to assist in the development of ultra-high density recording technologies. To be effective in evaluating optical recording systems, two key requirements for the spin stand is that it have the ability to focus on a multi-layer medium and is capable of utilizing a blue-light argon ion laser to characterize ultra-density experimental media. In order to meet these requirements a number of obstacles had to be overcome.

The first of these obstacles was in the ability of the spin stand to obtain a good carrier-to-noise ratio (CNR). The DSSC's first spin stand had a problem achieving a 63 dB CNR on a reference magneto-optic media supplied by IBM. The problem was ultimately tracked down to the argon ion laser itself. Inherent to gas lasers is a low frequency modulation noise. This modulation noise was aggravated by dirty laser optics and further exacerbated by a fiber optic channel used to conduct the light to the optical head. Once the laser was cleaned and the fiber optic cable eliminated from the light path the desired CNR was achieved.

The next obstacle to be overcome was in the spin stand's ability to automate the way in which it performed the CNR test. The first crucial modification implemented to address this was the replacement of an electro-optic modulator, used to modulate the laser intensity, with an acousto-optic. This modification allowed for better control of the modulation and allowed us to automate the testing procedure. Concurrent with this effort was a push to develop a focus servo system that would provide for multi-layer testing of experimental media.

Accomplishing this included the design and implementation of hardware control systems for the spin stand. The tracking servo on the blue wavelength optical media spin stand was modified to satisfy the requirements for an ultra-high recording density of greater than 10 Gbit/in2. To achieve this, soft sampled servo tracking was incorporated into the system. Soft sampled servo tracking is a method that requires sector marks to be written to a flat or ungrooved disk using the write laser. These sector marks can then be used for tracking in the same manner as pre-stamped servo marks. This will allow flat substrates to be used, but is difficult to implement at the desired density. In order to write the servo marks at the desired density with the write laser, the media positioning must be controlled very accurately. Therefore, the spindle position must also be closely controlled. To achieve this, a new spindle with very low run-out was integrated with an air slide. This allowed the spindle to be moved very precisely using a high resolution encoder and a voice coil. The configuration results in a minimum step size of 5 nm and a positioning error of 25 nm.

<u>Evaluation of Media Systems for Ultra-High Density Optical Recording</u>

Throughout the course of meeting the hardware requirements for the improvement and optimization of the blue wavelength optical spin stand, many samples of experimental magneto-optic, multilayer phase change and MSR media were tested and characterized. For magneto-optic media, comparison testing consisted of large and small mark recording CNR, noise classification, and thermal interference data relative to a commercial media standard. The comparison showed that the experimental media performed at a level similar to that for the commercial standard. For the large mark recording, the commercial standard had a 60.64 dB CNR with a carrier power of 7.80 dBm and a write noise power of 0.59 dBm. The experimental media had CNR data ranging from 44.56 dB to 59.88 dB, carrier powers ranging from 8.42 dBm to 13.16 dBm and write noise powers ranging from 0.02 to 1.41 dBm. Large mark recording was specified at a disk velocity of 10mps, a write width of 45 ns and a write pulse period of 1 MHz. In the small mark recording comparison, an experimental disk had a CNR of 54.05 dB, a carrier level of 3.42 dBm and a write noise level of 3.46 dBm as compared to the commercial standard which had a CNR of 53.53 dB, a carrier level of 0.60 dBm and a write noise level of 3.35 dBm. Noise classification used in determining the minimum write power needed to ensure a media noise dominated system, demonstrated that the experimental media needed less write power to become media noise dominated than did the commercial standard. Thermal interference testing indicated that an optimum write power of 20.909 mW was needed to effect a zero error mark size and that the media had a 10.638% interference level based on

a comparison of mark lengths between an isolated pulse and a double-pulse spaced a mark length apart.

Magnetic super resolution along with reading and writing to a multi-layer disk was demonstrated for the first time at the DSSC, using the improved optical spin stand and blue wavelength light. This work enabled examination of a large number of properties significant to MSR media. The formation of a read-out aperture was verified using the blue wavelength optical disk spin stand. A tri-layer magnetic super resolution disk using center aperture detection was tested on the blue wavelength optical disk spin stand. A rapid increase in the carrier-to-noise ratio as a function of incident laser power for the disk verified the formation of the thermal read-out aperture necessary for magnetic super resolution using center aperture detection. The size of the written mark could also be analyzed to demonstrate magnetic super resolution. This demonstration was performed by comparing the minimum written mark length possible on a standard magneto-optic disk to the minimum possible mark length on its magnetic super resolution counterpart. Compared to a conventional magneto-optic disk, the tri-layer magnetic super resolution disk had higher carrier-to-noise ratios for mark lengths smaller than the full width half maximum of the read-out laser. The tri-layer magnetic super resolution disk using center aperture detection was found to yield CNRs as large as 70 percent of the large mark CNR for marks as small as 0.2 microns.

The blue wavelength spin stand was also used to assist in the development of multi-layer phase change media, and allowed further development of focus servos for multi-layer media, the examination of inter-layer interference and large and small mark recording. Large and small mark recording was performed on both layers of multi-layer phase change media. The large marks were recorded using the following parameters; media speed of 10 m/s, write width of 350 ns and write frequency of 1 MHz. While the small marks were recorded using the following parameters; media speed of 6 m/s, write width of 50 ns and write frequency of 3.87 MHz. The large marks yielded a 48 dB carrier-to-noise ratio on the top layer and a 50 dB carrier-to-noise ratio on the second layer. The small marks yielded a 41 dB carrier-to-noise ratio on the top layer and 43 dB on second layer. All of the marks were read with a laser power of 1.2 mW. However, the marks on the top layer were written with a laser power of 20 mW while the second layer required 23 mW.

III. Conclusions

Research on ultra-high density optical recording systems funded by the U.S. Army Research Office was conducted at the Data Storage Systems Center at Carnegie Mellon University. The goal of this research was to supplement a broader DSSC effort to investigate optical recording technologies that could lead to ultra-high recording densities. In this effort, studies to identify the factors limiting the cyclability of phase change optical media have shown that cyclability is effected by the extent to which a recorded optical spot is heated when it is repeatably written and erased. A research effort to design, fabricate and implement a super-solid immersion lens system has allowed Center researchers to successfully develop the ability to fabricate SILs, both hemispheres

and superspheres. The research in this project has also provided for the improvement and optimization of the capabilities of a blue wavelenght optical spin stand to assist in the development of ultra-high density recording technologies. Throughout the course of meeting the hardware requirements for the improvement and optimization of the blue wavelength optical spin stand, many samples of experimental magneto-optic, multilayer phase change and MSR media were tested, characterized and reported.

IV. References

[1] Mann Du, Ph. D Thesis, Carnegie Mellon University, 1997.
[2] Aparna C. Sheila, Mann Du and Mark H. Kryder, "Dynamic Studies on Erasable Phase Change Media", Optical Data Storage Conference, Tucson, AZ, April '97.
[3] L. Cheng and M. Mansuripur, "Measurement of the thermal coefficients of erasable phase change media", Technical Digest of the Optical Data Storage Conference, April, '97.
[4] M.Libera, M. Chen, "Time resolved reflection and transmission studies of amorphous Ge-Te thin film crystallization", J. Appl. Phys., &3 (5), 2272, '93.
[5] J.H. Coombs, A.P.J.M. Jongenelis, W. van Es-Spiekman, B.A.J. Jacobs, "Laser induced crystallization phenomena in GeTe based alloys. 1. Characterization of nucleation and growth", J. Appl. Phys., 78 (8), 4906, '95.
[6] C. Peng, L. Cheng and M. Mansuripur, "Experimental and theoretical investigations of laser induced crystallization and amorphization in phase change optical recording media", J. Appl. Phys., 82 (9), 4183, '97.